Renewable and Sustainable Energy Reviews 13 (2009) 835–844

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of new technologies, models and experimental investigations of solar driers

M.V. Ramana Murthy *

Department of Mechanical Engineering, Osmania University College of Engineering, Osmania University, Hyderabad 500007, India

ARTICLE INFO

Article history:
Received 16 January 2008
Accepted 8 February 2008

Keywords:
Natural sun drying
Natural Convection
Solar tunnel drier
Food product

ABSTRACT

An attempt is made to review various aspects of solar driers applied to drying of food products at small scale. Popular types of driers in Asia-Pacific region, and new types of driers with improved technologies are discussed. The open sun drying and some alternate solutions are presented. The various aspects considered for modeling and experimental investigations carried out on various food products are also presented. Finally, the performance evaluation of the drier is discussed in detail. It is found that there is a shorter way of estimating the performance of a drier.

Contents

1. Introduction

Food is the basic comfort and necessity of living beings. The major problem faced by the mankind is, the balance of food production and consumption. Increase of food supply and limitation of population growth are cited as two solutions for the imbalance of food. But both the solutions require a considerable amount of capital and time to achieve. A third and most viable solution to the world's food problem involves reducing the food loss which occurs due to various reasons [1] in developing countries such as lack of suitable technology, improper cultivation and fertilization, lack of marketing channels, improper transportation, high post harvest losses, etc., causing a food loss from 10 to 40%. The food preservation is the only method to reduce the food loss and drying is the method that is being adopted since many centuries.

In case of vegetables, which is also an important food product, 50% of wet [2] vegetables (i.e., peels) are removed as waste while cooking. If the vegetables are peeled and the peels are dried, the peels/waste can be used to feed animals. Also, as the water is removed during drying, a lot of fuel can be saved during transportation of dry vegetables when compared to wet vegetables. The drying process of various products is explained in detail [3] and also some ideas on promotion of usage of driers to the Government and common public are suggested which could be of

* Correspondence address: H.No. 12-11-1276, Boudhanagar, Secunderabad 500061, Andhra Pradesh, India. Tel.: +91 9849323139.
E-mail address: mvramanamurthy@rediffmail.com.

1364-0321/$ – see front matter
doi:10.1016/j.rser.2008.02.010

Nomenclature

A	collector area of the dryer
I	hourly average solar radiation on the aperture surface
L	latent heat of vaporization of water at exit air temperature
LCV	lower calorific value of fuel and drier efficiency varies from 40 to 60%
m_b	mass of fuel consumed
P_f	energy consumption of fan/blower
W	weight of water evaporated from the product

use in Indian context. The drying of paddy, fruit, timber and cash crops are explained [4] in Indian context.

More than 80% of the food is produced by small farmers in the developing countries. These farmers dry the food products under the sun, i.e., natural sun drying is being practiced. Except that the solar energy is available for free, there are several disadvantages with the natural sun drying process. Some of the demerits include [5] degradation due to wind blown debris, rain, insect infestation, rodents, birds, over/under drying, etc. Further, due to prolonged drying, there is danger of aflatoxin [6] contamination of cereal grains. In other words the quality of the finished product is poor. Apart from the quality there exist some strange cases where natural sun drying cannot be adopted, e.g., cardamom cannot be sun dried as the sun [7] will fade the green color.

The process of drying is explained briefly [8]. At the start of the drying process the food produce is very damp, and its moisture content is the same inside and the surface: this is phase I. The moisture is present as on a free water surface. This is a surface evaporation phenomenon. As soon as the surface of the product has dried up, moisture has to migrate from the interior to the surface, where it can be evaporated: this is phase II. The energy required for this process is much more important than that used for the surface evaporation. This phase (phase II) depends on the particular food produce. The influence of temperature is critical to this process, as there exists a maximum allowable temperature for every food product, which is usually 15–20 °C higher than the ambient temperature.

In case of natural sun drying, the solar radiation heat is used to evaporate the moisture present in the product. As the sunshine is intermittent and varying, the product may over/under dry. Hence, the solar energy is used to heat large volumes of air and this air is allowed to flow over the products to remove the moisture and also take away. Such an equipment which uses solar energy to heat air and hence dry the food products is called as solar drier. A solar drier minimizes almost all the problems faced during natural sun drying, thus improving the quality of the dried product.

However, the quality characteristics of the finished product are also effected by the moisture content of the product after harvesting [1], the stage of maturity and contamination by microorganisms (which cannot be avoided) and by temperature, relative humidity, velocity of drying air, drying time, etc.

The description so far has been related to small farmers whose product to be dried is also small. In case of large scale farmers, commercial scale drying is adopted. Fuels such as coal, oil or wood are used for production of hot air in large scale. A company in Pune of India [7] has switched over from natural sun drying to commercial drying with diesel fuel. However, solar drying is proposed to replace fuel heating. The energy requirements for drying of sesame seeds is calculated and the energy supplied by solar heating is calculated to show that not all but most of the energy requirement by diesel fuel is replaced by solar heating. Economic analysis is also carried out to calculate pay back period. A commercial solar dryer [9] for small and marginal farmers of arid regions is developed which consists of inclined driers connected in series, so that the driers can face the direct sun rays for maximum exposure of sunlight. The drier is tested and economics is also worked out.

In some cases such as bio-energy plants, the bio-mass [10] may have to be dried, which will be always on commercial scale, due to continuous running of an engine or turbine. The principle of drying, factors effecting the drying, and types of industrial driers are explained in detail [10].

The other applications include space heating and ventilation [4]. Further, the pelargonidin [11] ethanoic extract can be obtained by solar drying from rose petals which can be used in economic production of cheap and reliable acid–base indicator for the use in chemistry laboratories. In spice technology, the oleoresins are responsible for the characteristics of taste or flavor. Although it is well known that essential oils can be used to replace most herbs and spices quite effectively, in terms of aroma, the oleoresin produces subtle roundness of the natural flavor. However, the oleoresin extracted from fresh thyme herbs [12] had a foul smell. The solar (sun) evaporation causes loss of flavor and aroma characteristics. So, these are solar dried and can be ground into powder to use as herb seasoning. The oleoresin which is also present in West Indian ginger [13] is present in form of organelles and is not observable in fresh ginger. The solar dried and solar dried/steam distilled ginger is used to increase the oleoresin extraction yield. The pungent principles of ginger, i.e., oleoresin which can be divided into gingerol and shogaol [14] are used in medicine and various purposes. The extraction of gingerol and shogaol using a pilot extraction plant is described. But, the gingerol:shogaol ratio was much higher for the solar dried ginger. The wire basket solar crop dryer used for solar drying of West Indian ginger is very efficient and cheap [15].

2. Types of solar driers

There are several types of driers developed to serve the various purposes of drying food products as per local need and available technology. After a survey of several countries in Asia-Pacific region [5], the best potential and popular ones are:

(i) natural convection cabinet type,
(ii) forced convection indirect type and
(iii) green house type.

Apart from the above three, as seen from the literature, "Solar tunnel drier" is also found to be popular and hence, included in the list. These conventional types are shown in Figs. 1–4.

2.1. Driers with improved technology

Apart from the above basic types, several driers have been developed with improved technology. A reverse flat plate absorber cabinet dryer [16] is developed (RACD) (see Fig. 5). The absorber plate is horizontal and downward facing. A cylindrical reflector is placed under it to introduce solar radiation from below. The area of the aperture is the same as that of the absorber plate. The cabinet dryer is mounted on top of the absorber to maintain a gap for air to flow above the absorber, which becomes heated and the hot air enters the dryer from the bottom. Firstly, hot air heats the crop spread over wire mesh and then moisture starts moving from the interior of the kernel to the surface and then to the chamber. Secondly, the moisture-laden air exits the chamber through the vent because of the vapor pressure

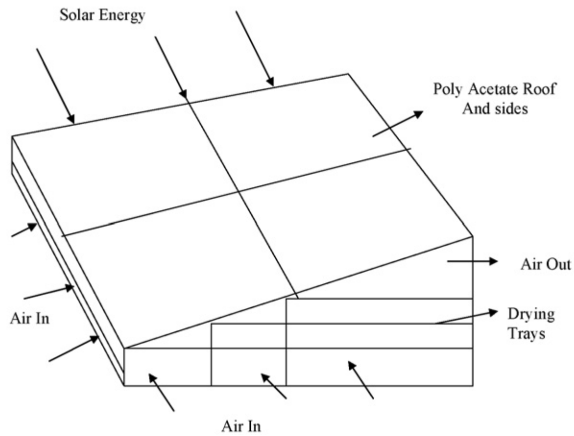

Fig. 1. Natural circulation type cabinet drier.

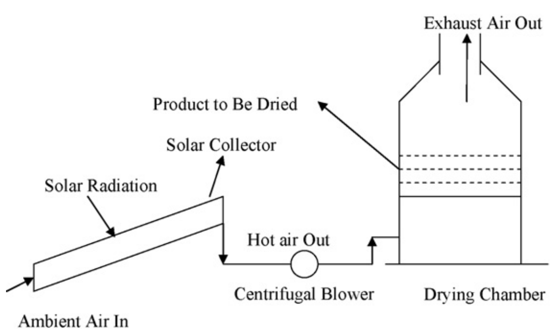

Fig. 2. Forced convection solar drier.

difference between the chamber and the outside, in the natural mode of operation.

A multi-shelf portable solar dryer [17] is developed. It has four main parts, i.e., multi-tray rack, trays, movable glazing and shading plate (see Fig. 6). The ambient air enters from the bottom and moves up through the material loaded in different trays. After passing through the trays, the air leaves from the top. The multi-rack is inclined depending upon the latitude of the location. Four layers of black HDP sheet are wrapped around the multi-rack such that heat losses are reduced to ambient air from back and sides.

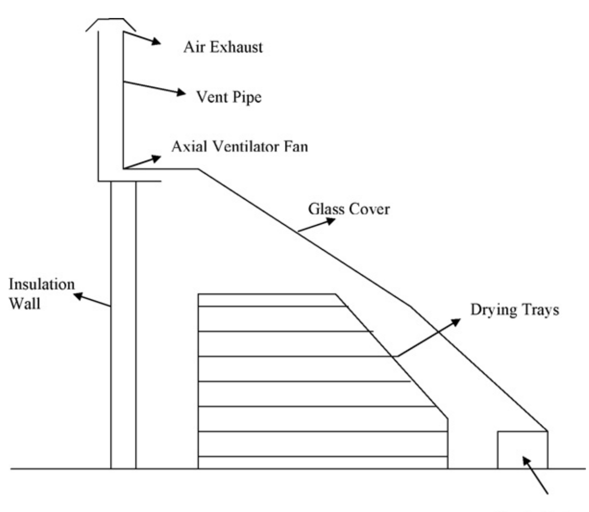

Fig. 3. Green house type solar drier.

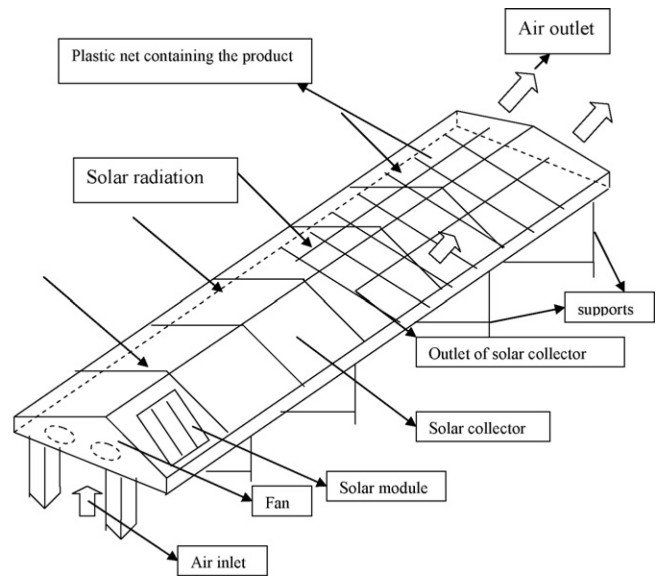

Fig. 4. Solar tunnel drier.

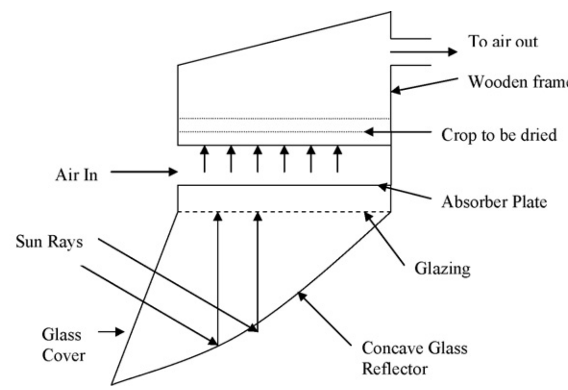

Fig. 5. Reverse absorber cabinet drier.

There are seven perforated trays, which are arranged at seven different levels one above the other. The product to be dried is loaded in these trays. To facilitate loading and unloading, a new concept of movable glazing has been developed. It consists of a movable frame (on castor wheels) and UV stabilized plastic sheet. After loading the product, the movable glazing is fixed with the multi-tray rack so as to avoid any air leakage.

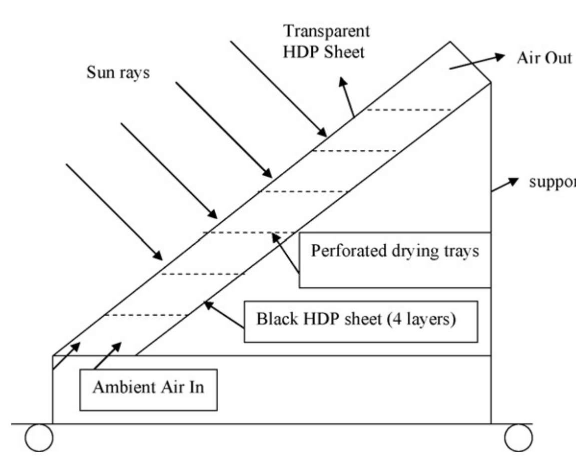

Fig. 6. Multiple-shelf portable solar drier.

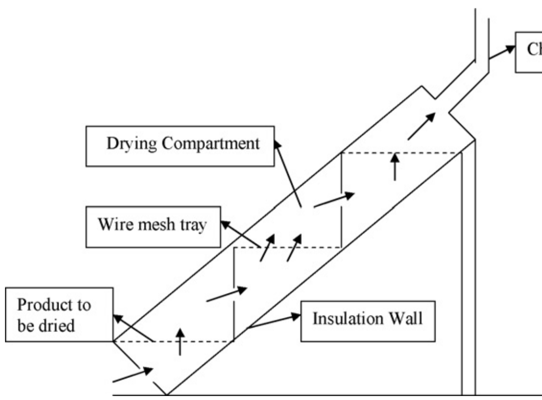

Fig. 7. Staircase solar drier.

A staircase type dryer [18] is developed which is in the shape of a metal staircase with its base and sides covered with double-walled galvanized metal sheets with a cavity filled with non-degradable thermal insulation (see Fig. 7). The upper surface is covered with transparent polycarbon sheet to allow the sun's rays to pass through and be trapped. The upper polycarbon glazed surface is divided into three equal parts which can swing open, to provide access to the three compartment inside the dryer. The base of the dryer has four entry points. The partition walls between the compartments also have four port holes for easy air flow. Air moves by natural convection as it enters through the bottom and leaves from the top.

Another system called rotary column cylindrical dryer [19] is developed which contains essentially three parts—air blow region (fan), air heater region (solar collector) and drying region (rotary chamber) (see Fig. 8). A fan with variable speed of air flow rate is connected to the solar collector using a tent fabric. The connection to the dryer or rotary chamber was again through another tent fabric. The dryer is manufactured from wooden plates at the top and bottom and thin ply wood plates at the sides to make cylindrical shape. A rectangular slot is opened on side wall where it faces the solar air heater for the passage of hot air via tent fabric. On the opposite side of this wall a door is provided for loading and unloading of the products. A column is constructed at the center of the rotary chamber to mount the products and the column rotates due to a 12 V dc motor and a pulley and belt system.

Other solar assisted drying systems are also developed [20]. The use of V-grooved absorbers improves the heat transfer coefficient between the absorber plate and the air. The present dryer uses collector of the V-groove absorber type (see Fig. 9(a)).

A double pass collector is also developed which consists of a porous medium [20] in the second pass to store the energy and supply during cloudy weather or in the evenings (see Fig. 9(b)).

Some have been improved further by using other methods such as increased convection, etc., which are briefly discussed below.

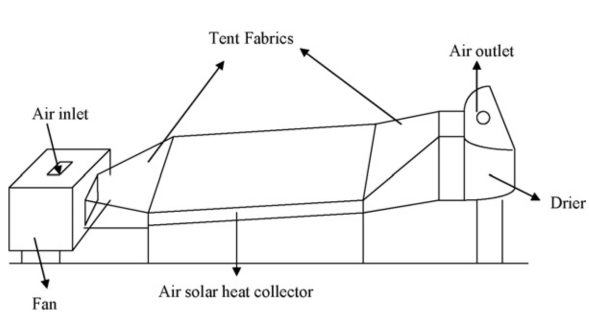

Fig. 8. Rotary column cylindrical drier.

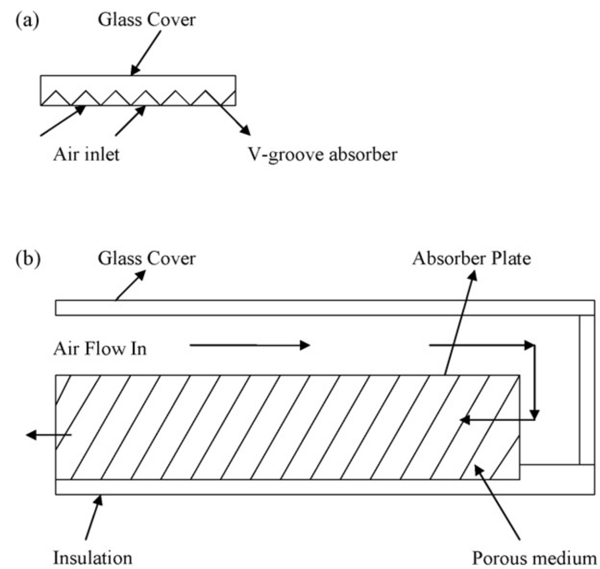

Fig. 9. Solar assisted drying systems.

Since the products need to be spread in a single layer for efficient drying, total tray area available in the dryer for spreading the product is important. In an attempt to acquire the area, the roof top [21] of a farm house has been used as a collector. In extension to this type of drier [22], a dual purpose of illuminating the room by providing a low temperature roof integrated solar flat plate air heater is introduced. The heated air is used to dry the food grains spread on perforated plates of aluminum and acrylic, inside the room. The perforation size for groundnut and paddy is calculated. In yet another method, a sun tracking system is used along with a dc driven solar fan [23] for a controlled heating of the product, as shown in Fig. 10. For example, maize requires to be heated below 60 °C to avoid overheating and microbial attack. A biomass backup heater is used to supplement the heat required for faster drying process [24].

Six different types of cabinet driers (all natural circulation type) are constructed with same fabrication materials [25] and absorber areas, but different height of air gaps, air pass methods and configurations of absorber plates. The air flow rate is maintained constant in all the cases. Out of all, the single covered/glazed and the front pass type with black painted aluminum sheet as absorber plate is found to be most efficient. Also, it is found that, the effect of the shape of the absorbing surface on the performance is considerably less.

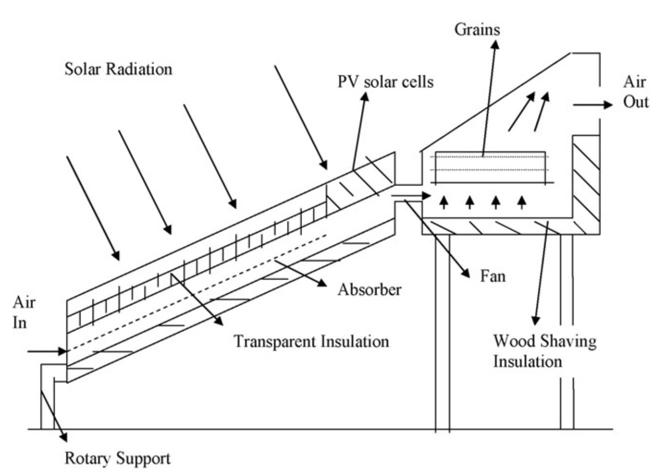

Fig. 10. Solar grain dryer with rotatable indirect air heater and a PV run fan.

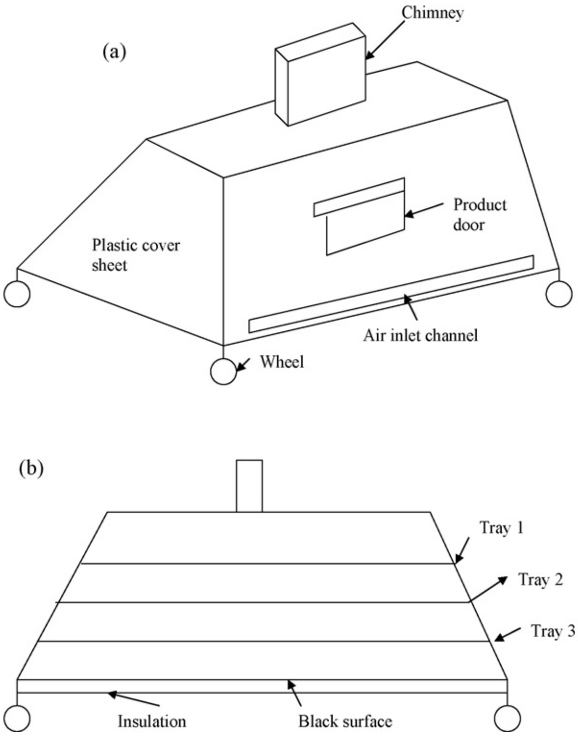

Fig. 11. (a) A simple presentation of first model and (b) side view of first model.

In order to make the driers cost effective and comparable to open sun drying, natural convection type green house driers [26] are developed and tested. There are two types of driers (see Figs. 11 and 12). The driers are tested without load–without chimney, with load–without chimney and with load–with chimney. When the driers are loaded (pepper in the present case), the efficiency reduces. It is found that the green house driers are increase the air temperature by 5–9 °C and the chimney provides better natural circulation of air.

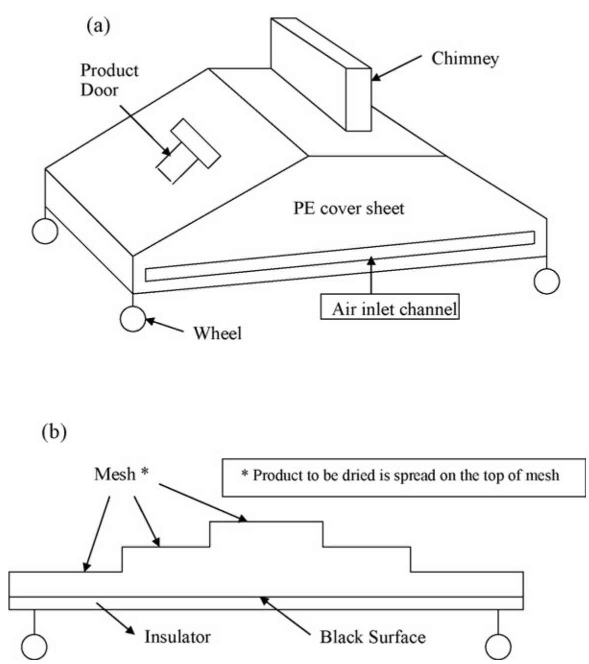

Fig. 12. (a) A simple representation of second model and (b) side view of internal representation of second model.

Totally different methods of drying have been developed which continue to dry the products even in the night times thereby reducing the drying time drastically. The desiccant materials [27] are used which absorb the moisture from the products to be dried. The cost of desiccant materials is high causing the final food product cost to be high. Hence, low cost desiccants [28] particularly suitable for tropical countries are identified as bentonite–calcium chloride and kaolonite–calcium chloride. Yet another type is the one with thermal storage (sensible) to take care of intermittent incoming solar radiation [29]. The length and width of the air heater, the gap between the absorber plate and glass cover and thickness of the storage material are optimized in this type of drier. The thermal efficiency of the air heater is found to be sufficient for drying of fruits and crops.

In all the types of driers stated above, the hot air enters the drying chamber and leaves to the atmosphere. But the hot air can be recirculated [30] to save the energy. The drying of coconut and cocoa in a scaled down drier of a large scale drier is considered in which the recirculation of hot air yields 31 and 29% of energy saving, respectively. The recirculation of exhaust/hot air is also applied to hay driers [31]. Lack of uniform drying and inability to accurately predict drying times are some of the existing problems. A new drier is developed which uses forced heated-air circulation through hay stacks. A drying rate difference of 7% is observed due to recirculation of hot air. By recirculating all of the exhaust air, the previous driers either increased drying time or proved to be uneconomical. So only 30% of the hot air is recirculated in the present case. The favorable conditions to recirculate the exhaust air are presented.

A drier called FASD (Foldable Agro Solar Dryer) is [32] developed which is a foldable type that can be stored and transported as desired. The performance of the drier is tested to find that the inner temperature is about 8 °C higher than ambient and humidity is lesser by 6% inside.

Out of all types, the well known heat pump [33] principle has been used to dry the products and this has been found to be excellent alternative to the solar drying.

3. Natural sun drying and some alternate solutions

The solar drying process in various types of driers discussed above is very frequently compared with natural sun drying as sun drying is adopted by nearly 80% of farmers (as the driers are a costly affair for those farmers). Hence, study of natural sun drying [34] of cassava, banana (ripe and raw) and mango is considered. The results of drying of all the three products have been compared with the previous works and amongst themselves. The main parameters used for the comparative study are—moisture content and maximum difference between ambient and sample temperatures. Also, some terms such as critical moisture content, drying rhythm (mass of sample at time "*t*"/initial mass of sample), mass transfer coefficient and "heat transfer coefficient/latent heat of evaporation" important for the drying process are discussed.

As next alternative to natural sun drying some driers are developed to serve the purpose of small scale farmers, as claimed by the authors. Out of those shell type [8,35] and modular type [36] driers are considered.

The shell drier is one of the earliest types used by Africans. The description and operation of the shell drier [8] is presented. The modeling of the drier is done. The model is experimentally validated against the data of previous workers. The size and distribution of bottom shell holes is optimized and the effect of thickness of the produce slice is established [35].

In modular type drier [36] a drier is constructed which works in combination with PV module. The modular type implies the ability of the drier to operate in natural ventilation of ambient air,

artificial ventilation when PV module is connected, artificial ventilation when pre-heater, i.e., solar air collector is applied and a combination of PV module and pre-heater. The parameters of air, which are effected by solar radiation, i.e., pressure, velocity and temperature difference are calculated and the efficiency of drier is also calculated using basic knowledge of heat transfer and fluid mechanics. The velocity of natural convection currents is measured experimentally.

4. Analysis and modeling of drying processes

The drying process has been experimentally studied and analyzed to simulate and design a drier. As drying is a process of removing moisture to a safe level, the equilibrium moisture content is defined [37] as the moisture content in equilibrium with the relative humidity of the environment. The equilibrium moisture content is divided into, static and dynamic. While the static is used for food storage process, dynamic is used for drying process. The drying process is experimentally obtained and presented as moisture content on x-axis and rate of drying on y-axis.

A deep bed of food grains is assumed to be composed of thin layers normal to the hot air flow direction. The equations for thin layer were written initially, using empirical, theoretical and semi-theoretical equations. The conditions of the grain and air, change with position and time during drying of a deep bed of grains. Logarithmic and partial differential equation models to simulate the deep bed dry modeling are dealt in detail.

A computer program in C++ language is developed for modeling of deep bed drying systems [38] and considers eight different configurations of flow of hot air over absorber plates of solar collectors. The usual parameters such as heat removal factor, overall loss coefficient, top loss coefficient, etc., can be determined. The model prompts for basic data such as amount of grain to be dried, initial moisture content, number of thin layers and weather data. The results of drying of rough rice are presented.

In a different direction, the first and second law of thermodynamics [39] have been used to develop the design methods for a particular application. Semi-empirical formulae are developed to calculate the rise in air temperature as it passes through the heater. NTU (number of transfer units) has been defined analogous to the heat exchangers, as a part of design. Using entropy balance the maximum temperature reached by solar collector is written and then Entropy Generation Number is developed to find the entropy generated during thermal conversion of solar energy. Finally, the drying temperature is established as a function of the maximum limit of temperature the fruit might support.

The drying chamber of a drier consists of meshes on which the food product is spread for drying. Also, the drying chamber [40] is a wooden cabinet. Hence, the heat loss to the side walls of the drying chamber is considered. As the hot air passes through the mesh, in forced convection driers, turbulence is created. A solar drier without either heat storage or air recycling is considered with a solar collector containing offset plate fins. Experiments are conducted to calculate heat losses (through Nusselt number).

In the above models, the variation of incoming solar radiation is not taken into account. For modeling purpose, a constant artificial flux [41] is adopted to study the drying phenomenon. A drier with three beds of wool is considered with a solar collector. The drying process in the three zones of the bed is theoretically analyzed. The solar collector is equipped with a flat plate absorber and offset plate fins absorber plate. Under constant incident fluxes, at the same mass flow rate of air, the drying rate and time has been studied to find that offset plate fins collector is better.

The known facts that, the inlet temperature of the air is variable (because of variable incoming solar radiation) and the food products shrink as drying process continues are taken into consideration [42] for modeling. A most common cabinet type drier is considered for the study. A moving co-ordinate is defined to take into account of the shrinkage effects. The experimental data from previous workers is considered for validation of the mathematical model. The carrot cubes are used as food product to test the model.

It is proposed that the estimation [43] of solar irradiance on the drier is essential to predict the response of the drier. Considering a semi-cylindrical solar tunnel drier, the irradiance is calculated by taking the geometric quantities, relative motion of sun and optical properties into account. The model is tested in winter and summer in India.

The change of main variables such as moisture content along the drying tunnel is considered unlike in previous works where uniform distribution is assumed [44]. This is a study of tunnel green house drier which is continuous type. The conditions for improvement of efficiency are evaluated. A linear relationship between the tunnel output temperature and incident solar radiation is obtained. The drier production is presented by a performance parameter which is defined as the ratio between the energy actually used in the evaporation and the total available energy for the drying process. A non-dimensional variable is also defined, which has all the meteorological information. It is found that, the average moisture content value of the tunnel can be considered to be constant.

A tunnel drier is tested for drying of chillies [45]. As stated earlier, in some cases natural solar drying cannot be used as it decolorizes the product. Drying of chillies is one such case. As natural convection driers effect the quality of the product due to low buoyancy effect and other types of driers are costly, e.g., tunnel drier, the drying process is simulated and economic model is also developed. Optimum designs are obtained. The design geometry is found to be sensitive to cost of major construction materials of the collector, solar radiation and air velocity in the drier.

5. Experimental investigations on applications of solar driers

As stated in introduction of this paper, "there exist some factors such as moisture content of product after harvesting, the stage of maturity and contamination by microorganisms which affect the quality characteristics of the final product. All these parameters depend upon the type of the product being dried." Hence, experimental investigations are being carried out to study the drying behavior of various food products. This has lead to several articles in the literature related to solar drying.

The dehydration of food products is considered to calculate the quantity of air needed for drying [46], depth of food bed, height of chimney and pressure difference across the food bed. Psychrometry is used to determine the thermal energy to be removed for drying cassava to desired moisture level. Considering a bed of cassava the area of collector and the depth of the bed is calculated for the drying process. A drier is constructed with sensible type rock storage system to continue the drying process in the nights. The temperature, humidity and variation of moisture content are plotted with respect to time on a given day for cassava leaves. The drying process is described by an empirical equation. The drying constants for constant- and falling-rate periods [38] are tabulated for cassava chips, pepper and groundnuts.

It is stated that, the quality of open-sun dried product is poor. One of such parameters to measure the quality of the product is, retention of ascorbic acid for potential preservation of all other nutrients. Hence, it is proposed to develop a drier to retain ascorbic acid [47]. The drier is made of removable absorber plates

which are made of different materials to obtain the desired collector outlet temperature. The drying energy requirements and pressure drop across the food bed are calculated using psychrometric methods. Mangoes are used for testing purpose. An empirical equation is developed between time of the day and relative humidity. The collector efficiency is calculated and it is found that metallic absorbers are more efficient than wooden absorber. But, wooden absorber is preferred as it is cheap and readily available in tropical countries. It is found that, the acidity of solar dried mangoes is higher indicating resistance to the spoilage due to microorganisms. However, the ascorbic acid retention percentage is found to be high by solar drying but with a high variation (i.e., $\pm 22\%$).

Despite repeated claims that the solar dried food products are superior in quality to natural sun dried products [48], various tests were conducted to assess the quality of products. The tests included determination of final moisture content, percent ash, sugars, ascorbic acid, acidity and sensory evaluation. These parameters were measured for grapes, figs, tomatoes and onions and compared in the three cases of natural sun drying, solar mixed and solar indirect drying processes. The sensory evaluation of color, texture and flavor were carried out by untrained panelists.

In order to introduce the driers to the farmers, the suitability of driers for fruits and vegetables is tested by three types of driers [49] and those are cabinet type natural convection solar drier, a multi-stacked natural convection solar drier and an indirect type multi-shelf forced convection solar drier. The products chosen for study are mushrooms, green chillies and tomatoes. It is found that, the quality of dried product is more or less same in all the three cases of driers. A discussion about the selection of a drier for a particular application is carried out.

The drying of bananas in hot and humid weather conditions [50] in a solar tunnel drier under forced convection conditions is considered. The construction and working of solar tunnel drier is explained in detail. Three fans run by a solar module are used to create forced convection. The drying procedure and the instrumentation are also described. The major advantage of solar tunnel drier is that the regulation of the drying temperature is possible. During high insolation periods, more energy is received by the collector, which tends to increase the drying temperature and is compensated by the increase of the air flow rate. The variation of voltage with respect to radiation in a given day and variation of radiation with respect to time of the day are presented. The comparative curves using the tunnel dryer and natural sun drying are presented to show that, the tunnel drying time is less. A substantial increase in the average sugar content is observed. The economics of the drier is worked out to show that, the pay back period is 3 years.

Similarly, the drying of pineapples is carried out [51] in the solar tunnel drier. The contribution is the variations of air temperature along the length of solar tunnel drier for an experimental run, which indicates that almost uniform drying of pineapple slices is possible in a tunnel drier.

The solar tunnel drier is modified to develop a green house tunnel drier [52] whose working principle and construction is explained in detail. Some additional features of the tunnel drier are high lighted such as improvement in the drier efficiency, lowering of the labor cost and ease in installing a conventional heater as an auxiliary heating system for continuous production. The drier is considered as a solar collector, and its instantaneous efficiency is measured. The drier is used to dry red sweet pepper and garlic. Both the food products were dried in various configurations, i.e., cut in various ways. The plots of time in a given day vs. moisture content are plotted. The working principle of auxiliary heating system is also presented.

Green gage is a famous fruit in China which is dried and consumed [53]. A usual solar drier with air heater and drying chamber is considered with three air heaters in parallel. The salted green gages were simultaneously dried in the drier and in natural sun. It is seen that the daytime average temperature rise in the drying air inside the chamber was at 18–19 °C. In solar drying, the salt present in the green gages has diffused to surface and crystallized making it easier to desalt the product, whereas in natural sun drying, 20 days had to be spent in desalting by fermentation. When the rainy weather persisted, solar dried gages regained moisture slightly when compared to natural sun drying. However, the drying in the solar drier is not uniform and required exchanging of trays within the drying chamber. Also, the thermal efficiency is found to be very low indicating that the air at the outlet still had drying potential that needs to be used.

Some other applications of solar drying are given below.

The palm oil fronds are chopped, dried, ground and made into pellets [54] which are used as animal feed stock. Solar drying is adopted. A double pass collector which is of batch type is considered, which is yet to be constructed. A steady state one-dimensional analytical model is developed to calculate the outlet temperature of the collector and efficiency of the drier.

Natural rubber is used in some industries. As the rubber wood is being used to make furniture and wood chips, the cost of wood has increased. So, solar drying is adopted [55]. To develop a simple method for sizing solar assisted natural rubber dryers is main aim. The determination of collector area at an optimum level from economic view point is important in design of dryers. For this purpose the climatic data of long term should be available which can be obtained only by recording the climatic conditions over years. This is impractical and no model can duplicate the data. Hence, a simplified method is attempted which consists of deriving an empirical relation between solar fraction and design parameters which are collector heat gain and heat load. An integral equation for solar fraction is developed. The thermal performance of air collectors indicates that configuration of collector array plays an important role and to estimate the system performance, the collector array, i.e., parallel or series needs to be taken into account. During peak sunshine hours, the extra heat generated is dumped and the energy collection equation is adjusted for this dumping. For rubber sheet drying, a design parameter Y is defined and the relation between solar fraction and the term are plotted to see that, at low values of Y there is no heat dumping. In case of granulated rubber drying, no dumping is observed as drying occurs at high temperature.

Through out the literature, decrease in drying time has been the main concern. Further, the natural convection type drier is not preferred as low buoyancy forces may cause reverse effect leading to the spoilage of the food product. In order to resolve these two issues, an integral type natural convection drier coupled with a biomass stove is developed [56]. The drier is tested with three types of food products viz., ginger, turmeric and guduchi under three conditions, i.e., open sun drying, only solar and solar-biomass. The constructional details and operation of the drier are presented in detail. Drying time was lowest for solar-biomass method. The uniformity of drying was questionable as there was significant variation in moisture content when samples were tested from trays at top, middle and bottom. Even within a tray, when temperature, relative humidity and velocity of air were measured, variations were observed. The quality of finished products were tested for volatile oil and bitter content and it is found that, the quality of solar-biomass and only solar products were almost same. The drying efficiency of the drier was evaluated and it is noted that, type of product and its final moisture content level influences the drying efficiency.

The final moisture in a product generally requires more energy to extract than the initial moisture and the preparation of the products prior to drying such as slicing, boiling affects the drying efficiency. These factors make it difficult to make comparisons with the drying efficiencies of other solar driers reported in the literature.

Also, solar drying is used for sludge drying [57] and commercial high quality hay [58] production.

6. Performance evaluation

As can be seen from the above analysis, all the dryers are tested against moisture removal and one or two other aspects. However, a comprehensive method is evolved to standardize and compare all the driers developed [59].

The parameters generally reported are:

(a) Physical features of the dryer—The physical size of a dryer is often a direct measure of the drying capacity which usually means batch drying capacity, and refers to the quantity dried in a single batch of loading, measured in kg fresh product per batch. Generally, the size of the dryer indicates its drying capacity. For a given dryer, the drying capacity varies with the type of product and amount of moisture to be removed. Based on the type of product, e.g., bananas, batch drying may have to be switched over to continuous drying. The other factors such as collector area, size of drying chamber and air flow may also effect the drying capacity.

(b) Thermal performance—Drying time within a permissible maximum temperature (so as not to loose color, flavor, aroma, vitamins, etc.) from the loading of fresh product to drying to desired moisture level in hours or days is usually reported. Drying time w.r.t. moisture removed from the product when reported as graph is called drying rate. Drying air temperature is important as higher drying temperature at the beginning as well as the ending would effect the quality of product. The optimum drying temperature of various products are available in tabulated form in the literature. Relative humidity is yet another term reported in a different manner, i.e., drying potential where if the exit air from the drying chamber still has potential to dry is mixed with fresh air and recirculated to reduce the drying energy. The air that is recirculated is expressed in form of percentage.

An optimum air flow rate is essential as slower air flow rate may increase drying air temperature and a higher air flow rate may decrease the moisture removed. 0.75 m^3/min per m^2 of tray area is considered to be optimum. Drier efficiency is expressed as,

$$\frac{WL}{IA + P_f + (m_b \times \mathrm{LCV})}$$

where W is the weight of water evaporated from the product; L is the is latent heat of vaporization of water at exit air temperature, I is the hourly average solar radiation on the aperture surface; A is the collector area of the dryer; P_f is the energy consumption of fan/blower; m_b is the mass of fuel consumed; LCV is the lower calorific value of fuel and drier efficiency varies from 40 to 60%.

(c) Cost of the dryer and payback period.

(d) Quality of the dried product.

The quality of the dried product, i.e., nutritional attributes, color, texture, aroma, etc., have been poorly and inconsistently reported.

Hence, the present procedure proposes [14] improvements (i.e., standard procedures) over existing evaluation methods as follows:

(i) Rehydration—The ability of the dried product to regain its original volume when soaked in water is a measure of the product quality. The recommended way of determining is,

$$\text{Rehydration capacity} = \text{water absorption capacity} \times \text{dry matter holding capacity}.$$

(ii) Sensory evaluation, i.e., evaluation of color, evaluation of taste and aroma—The color is evaluated using Munsell color-order system. The taste and aroma are evaluated after a detailed methodical process is carried out in cooking and the cooked products are tasted by a test crew. Their opinions are expressed in form of stars from single star–poor quality to five stars–best quality.

(iii) Chemical tests—The heat and air in the process of drying effect the nutritive values such as vitamin A and C, B-complex, etc. In the present system, the retention of vitamin C and beta-carotene are given higher weightage in terms of stars. The other parameters are ash content, total sugar content and acidity.

(iv) Drying time required to reach 15% product moisture content—As stated earlier time taken for drying is important parameter of comparison of dryers. Hence, time taken for reduction of moisture level to 15% (w.b.) of its original value is considered for most fruits and vegetables.

(v) Drying system efficiency during drying up to 15% product moisture content is considered to be consistent for comparison.

(vi) Loading density per unit area of solar aperture.

The loading density is to load the fresh product into a dryer. A cabinet dryer has got higher loading density as several trays can be staggered when compared to other types of driers. Hence, loading density per unit area of solar aperture is considered.

(vii) As there exists socio-economical factors of local nature, some additional parameters are also considered for evaluation:

a. Solar aperture—The solar collector area (to heat air) and as in some mixed-mode dryers solar radiation is also received the total area available for solar radiation is considered.
b. First day drying efficiency—There exist two types of drying, i.e., constant- and falling-rate drying and a product under drying switches over from first to next causing inconsistency in evaluation. However, as on the first day of drying, all the products remain in constant rate, the drying efficiency is considered to be consistent.
c. Maximum drying temperature at no load and with load—As fruits and vegetables are temperature sensitive products, it is essential to maintain a range of temperature and hence, the maximum temperature is essential to be noted for no-load and with load.
d. Duration of drying air temperature 10 or 15 °C above ambient—Under similar radiation levels, efficiency values for two dryers can be similar even if the air flow rates are different. But the temperature of drying air affects the efficiency directly. Since, a temperature rise of over 10–15 °C is preferred in view of nutritive values, duration of existence of temperature 10–15 °C above is important.
e. Loading and unloading time is dependent on the design of dryer and is a direct expense of labor and hence this factor is also considered.

The thermal efficiency, which is commonly used as performance parameter is found to be misleading [60], when particular

use with the preheated air is considered, i.e., when air flow rate to collector area ratio is considered. A numerical example showing a real case is presented to make the fact clear. Hence, a new index called "Evaporative Capacity" is defined as

$$\text{Dry air flow rate} \times (\text{drier outlet absolute humidity when air leaves the drier in equilibrium with the product} - \text{ambient absolute humidity})$$

This index helps to evaluate the influence of meteorological conditions on solar drier performance. Charts are developed to calculate Evaporative Capacity.

7. Conclusions

It is found that, various types of driers are available to suit the needs of farmers. The dependence of the drying on the characteristics of product remains still as a problem, for comparison of drying efficiencies of various driers. The performance evaluation procedure of driers can be simplified by using "Evaporative Capacity" concept.

References

[1] Esper A, Muhlbauer W. Solar drying—an effective means of food preservation. Renewable Energy 1998;15:95–100.
[2] Wahidi R, Rohani AA. The benefits of solar dryers in Iran. WREC 1996; 700–2.
[3] Oztekin S, Bascetincelik A, Soysal Y. Crop drying programme in Turkey. Renewable Energy 1999;16:789–94.
[4] Bansal NK. Solar air heater applications in India. Renewable Energy 1999;16:618–23.
[5] Ong KS. Solar dryers in the Asia-Pacific region. Renewable Energy 1999;16:779–84.
[6] Thoruwa TFN, Smith JE, Grant AD, Johnstone MC. Developments in solar drying using forced ventilation and solar regenerated desiccant materials. WREC 1996;686–9.
[7] Hollick JC. Commercial scale solar drying. Renewable Energy 1999;714–9.
[8] Fournier M, Guinebault A. The shell dryer—modeling and experimentation. Renewable Energy 1995;6:459–63.
[9] Thanvi KP. Development of a commercial solar dryer for arid regions. In: Proceedings of the national solar energy convention; 1998. p. 289–94.
[10] Brammer JG, Bridgwater AV. Drying technologies for an integrated gasification bio-energy plant. Renewable Sustain Energy Rev 1999;3:243–89.
[11] Balladin DA, Headley O. Solar drying of rose (*Rosa* sp.) petals. Renewable Energy 1999;18:249–55.
[12] Balladin DA, Headley O. Evaluation of solar dried thyme (*Thymus vulgaris* Linne) herbs. Renewable Energy 1999;17:523–31.
[13] Balladin DA, Headley O, Chang-yen I, Duncan EJ, McGaw DR. Comparison of the histology of (I) fresh, (II) solar dried and (III) solar dried/steam distilled ginger (*Zingiber officinale* Roscoe) rhizome tissue prior to the extraction of its pungent principles. Renewable Energy 1999;17:207–11.
[14] Balladin DA, Headley O, Chang-yen I, McGaw D. Extraction and evaluation of the main pungent principles of solar dried West Indian ginger (*Zingiber officinale* Roscoe) rhizome. Renewable Energy 1997;12:125–30.
[15] Balladin DA, Chang-yen I, McGaw DR, Headley O. Solar drying of West Indian ginger (*Zingiber officinale* Roscoe) rhizome using a wire basket dryer. Renewable Energy 1996;7:409–18.
[16] Goyal RK, Tiwari GN. Parametric study of a reverse flat plate absorber cabinet dryer: a new concept. Solar Energy 1997;60:41–8.
[17] Singh S, Singh PP, Dhaliwal SS. Multi-shelf portable solar dryer. Renewable Energy 2004;29:753–65.
[18] Hallak H, Hilal J, Hilal F, Rahhal R. The staircase solar dryer: design and characteristics. Renewable Energy 1996;7:177–83.
[19] Sarsilmaz C, Yildiz C, Pehlivan D. Drying of apricots in a rotary column cylindrical dryer (RCCD) supported with solar energy. Renewable Energy 2000;21:117–27.
[20] Othman MYH, Sopian K, Yatim B, Daud WRW. Development of advanced solar assisted drying systems. Renewable Energy 2006;31:703–9.
[21] Janjai S, Tung P. Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices. Renewable Energy 2005;30:2085–95.
[22] Shanmugam S, Diana AH. Experimental study of dual purpose roof integrated low temperature solar flat plate thermal collector as agricultural dryer. In: Proceedings of the 26th national renewable energy convention of Solar Energy Society of India and international conference on new millennium—alternative energy solutions for sustainable development. PSG Tech., Coimbatore, India; 2002. p. 98–102.
[23] Mumba J. Development of a photovoltaic powered forced circulation grain dryer for use in the tropics. Renewable Energy 1995;6:855–62.
[24] Bena B, Fuller RJ. Natural convection solar dryer with biomass back-up heater. Solar Energy 2002;72:75–83.
[25] Koyuncu T. Performance of various design of solar air heaters for crop drying applications. Renewable Energy 2006;31:1073–88.
[26] Koyuncu T. An investigation on the performance improvement of greenhouse-type agricultural dryers. Renewable Energy 2006;31:1055–71.
[27] Shanmugam V, Natarajan E. Experimental investigation of forced convection and desiccant integrated solar dryer. Renewable Energy 2006;31: 1239–51.
[28] Thoruwa TFN, Johnstone MC, Grant AD, Smith JE. Novel, low cost $CaCl_2$ based desiccants for solar crop drying applications. Renewable Energy 2000;19:513–20.
[29] Aboul-Enein S, El-Sebaii AA, Ramadan MRI, El-Gohary HG. Parametric study of a solar air heater with and without thermal storage for solar drying applications. Renewable Energy 2000;21:505–22.
[30] McDoom IA, Ramsaroop R, Saunders R, Tang Kai A. Optimization of solar crop drying. Renewable Energy 1999;16:749–52.
[31] Schoenau GJ, Arinze EA, Sokhansanj S, Trauttmansdorff FG. Evaluation of energy conservation potential by exhaust air recirculation for a commercial type heated air batch hay drier. WREC 1996;676–81.
[32] Potdukhe PA, Thombre SB. Design, fabrication and performance of foldable agro solar dryer. In: Proceedings of the 26th national renewable energy convention of Solar Energy Society of India and international conference on new millennium—alternative energy solutions for sustainable development. PSG Tech., Coimbatore, India; 2002. p. 144–7.
[33] Best R, Cruz JM, Gutierrez J, Soto W. Experimental results of a solar assisted heat pump rice drying systems. WREC 1996;690–4.
[34] Siaka T, Nkembo SK. Comparative study of natural solar drying of cassava, banana and mango. Renewable Energy 2004;29:975–90.
[35] Fournier M, Guinebault A. Modeling and experimentation of the "shell" dryer. WREC 1996;682–5.
[36] Farkas I, Seres I, Meszaros CS. Analytical and experimental study of a modular solar dryer. Renewable Energy 1999;16:773–8.
[37] Bala BK. Solar drying systems: simulations and optimization, 1st ed., Udaipur 313002, India: Agrotech Publishing Academy; 1998.
[38] Dubey OP, Pryor TL. A user oriented simulation model for deep bed solar drying of rough rice. WREC 1996;695–9.
[39] Torres-Reyes E, Gonzalez NJJ, Ibarra-Salazar BA. Thermodynamic method for designing dryers operated by flat plate solar collectors. Renewable Energy 2002;26:649–60.
[40] Youcef-Ali S, Desmons JY, Daguenet M. The turbulence effect of the airflow on the calorific losses in foodstuff dryers. Renewable Energy 2004;29:661–74.
[41] Hachemi A, Abed B, Asnoun A. Theoretical and experimental study of solar dryer. Renewable Energy 1998;13:439–51.
[42] Ratti C, Mujumdar AS. Solar drying of foods: modeling and numerical simulation. Solar Energy 1997;60:151–7.
[43] Garg HP, Kumar R. Studies on semi-cylindrical solar tunnel dryers: estimation of solar irradiance. Renewable Energy 1998;13:393–400.
[44] Condori M, Saravia L. Analytical model for the performance of the tunnel-type greenhouse drier. Renewable Energy 2003;28:467–85.
[45] Hossain MA, Woods JL, Bala BK. Optimisation of solar tunnel drier for drying of chilli without color loss. Renewable Energy 2005;30:729–42.
[46] Ayensu A. Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy 1997;59:121–6.
[47] Madhlopa A, Jones SA, Kalenga Saka JD. A solar air heater with composite-absorber systems for food dehydration. Renewable Energy 2002;27:27–37.
[48] Gallali MY, Abjunah SY, Bannani FK. Preservation of fruits and vegetables using solar drier: a comparative study of natural and solar drying, III; chemical analysis and sensory evaluation data of the dried samples (grapes, figs, tomatoes and onions). Renewable Energy 2000;19:203–12.
[49] Sharma VK, Colangelo A, Spagna G. Experimental investigation of different solar dryers suitable for fruit and vegetable drying. Renewable Energy 1995;6:413–24.
[50] Schirmer P, Janjai S, Esper A, Smithabhindu R, Muhlbauer W. Experimental investigation of the performance of the solar tunnel dryer for drying bananas. Renewable Energy 1996;7:119–29.
[51] Bala BK, Mondol MRA, Biswas BK, Das Chowdury BL, Janjai S. Solar drying of pineapple using solar tunnel drier. Renewable Energy 2003;28:183–90.
[52] Condori M, Echazu R, Saravia L. Solar drying of sweet pepper and garlic using the tunnel greenhouse drier. Renewable Energy 2001;22:447–60.
[53] Zhimin L, Hao Z, Runsheng T, Tao L, Wenfeng G, Zhang Y. Experimental investigation on solar drying of salted greengages. Renewable Energy 2006;31:837–47.
[54] Supranto SK, Daud WRW, Othman MY, Yatim B. Design of an experimental solar assisted dryer for palm oil fronds. Renewable Energy 1999;16:643–6.
[55] Pratoto A, Daguenet M, Zeghmati B. Sizing solar-assisted natural rubber dryers. Solar Energy 1997;61:287–91.
[56] Prasad J, Vijay VK. Experimental studies on drying of *Zingiber officinale*, *Curcuma longa* and *Tinospora cordifolia* in solar-biomass hybrid drier. Renewable Energy 2005;30:2097–109.

[57] Luboschik U. Solar sludge drying—based on the IST process. Renewable Energy 1999;16:785–8.
[58] Arinze EA, Schonau GJ, Sokhansanj S. Design and experimental evaluation of a solar dryer for commercial high-quality hay production. Renewable Energy 1999;16:639–42.
[59] Leon MA, Kumar S, Bhattarcharya SC. A comprehensive procedure for performance evaluation of solar food dryers. Renewable Sustain Energy Rev 2002;6:367–93.
[60] Jannot Y, Coulibaly Y. The "Evaporative capacity" as a performance index for a solar drier air heater. Solar Energy 1998;63:387–91.